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Title:	Development of a pixelated BaF2 test bed for timing applications
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Development of a pixelated BaF_2 test bed for timing applications

Tyler Jordan

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LA-UR-xx-xxxxx

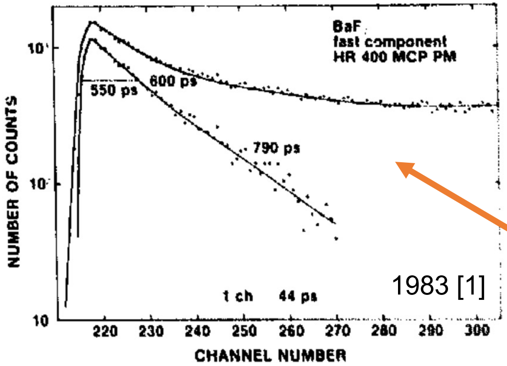
Outline

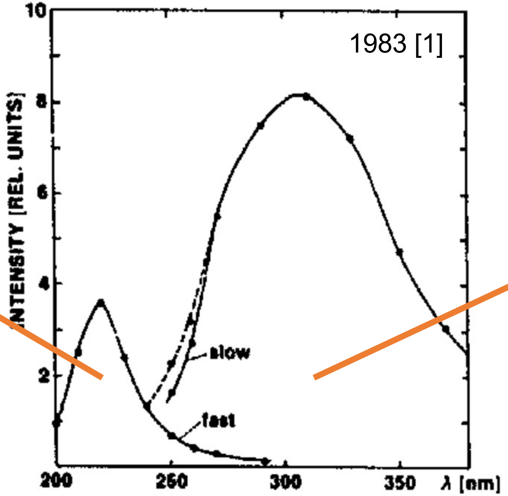
- Motivation: What can BaF_2 do?
- Background: How does BaF_2 do it?
- Focus: Time-of-flight positron emission tomography (TOF-PET)
- Prototype development: Design considerations
- Prototype development: Components and assembly
- Next Steps: Characterizing detector performance

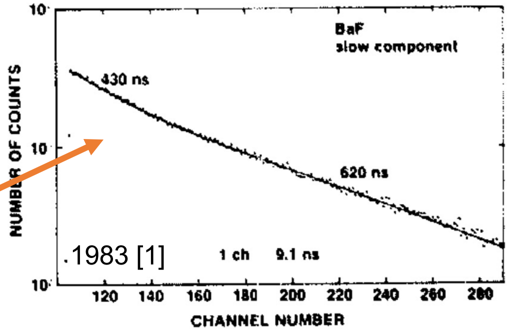
Introduction

Motivation

- BaF_2 one of the fastest known scintillators, emitting at 195 & 220 nm with sub-nanosecond decay constant
- Fast emission only comprises ~13% of total light
  - Most light is emitted at 310 nm, 600 ns decay constant
  - Count rate permitting → fast component for timing, slow component for energy resolution
  - High count rate → pile up







Motivation

Medical imaging
- Time-of-flight positron emission tomography (TOF-PET)
- Hadron therapy range monitoring

Low energy physics
- Neutron capture cross section measurements
- Nuclear lifetime measurements

Timing applications
- High time resolution
- High count rate

Materials science
- Positron annihilation spectroscopy

High energy physics
- Calorimetry

Motivation

- Ongoing BaF_2 research largely focuses on material and/ or photodetector characterization → small, single crystals
- Different applications require different detection system geometries
- Some applications require slow component rejection

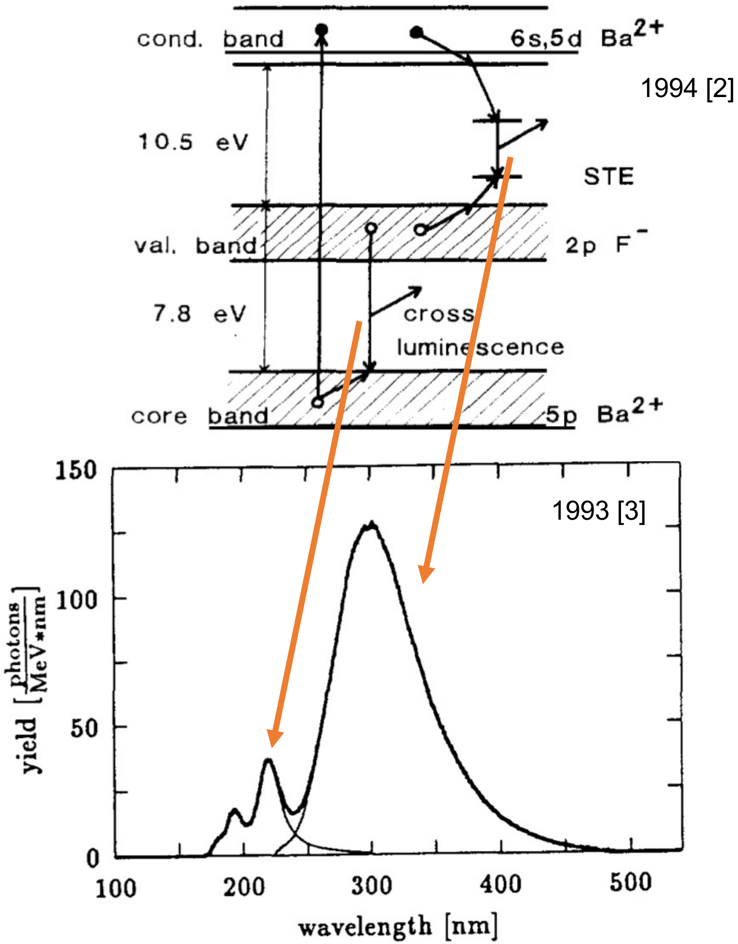
Goal: Develop a pixelated BaF_2 test bed to characterize the performance of various configurations for timing applications.

- Focus: TOF-PET → design inspiration
- Deployable form factor
- Variable system geometry

Background

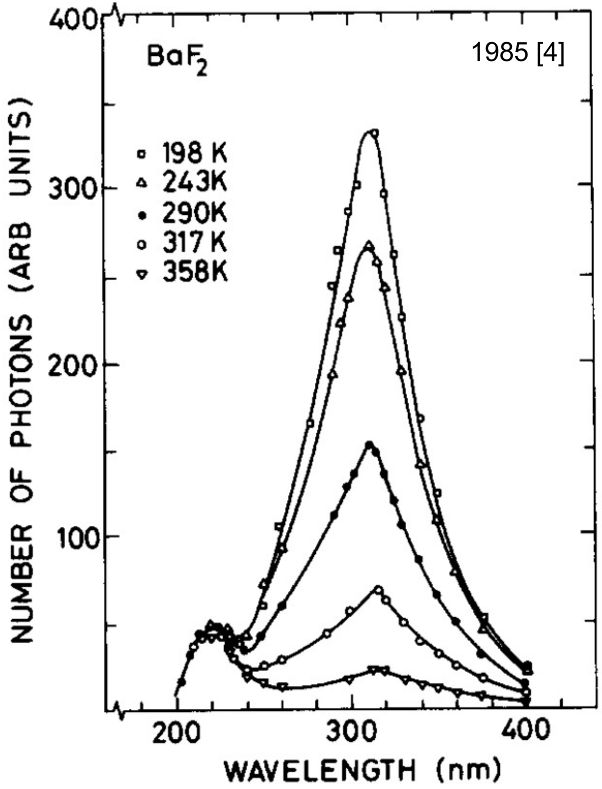
BaF_2 scintillation mechanisms

- Slow component
  - Self-trapped exciton (STE) luminescence
  - Self-trapped hole: two adjacent F^- ions share a hole, effectively forming F_2^-
  - A self-trapped hole captures an electron, forming a self-trapped exciton which subsequently decays
- Fast component
  - Core-valence (CV) luminescence
  - An electron from the $5pBa^{2+}$ band is excited to the conduction band
  - The hole left behind is quickly annihilated by an electron from the $2pF^-$ band



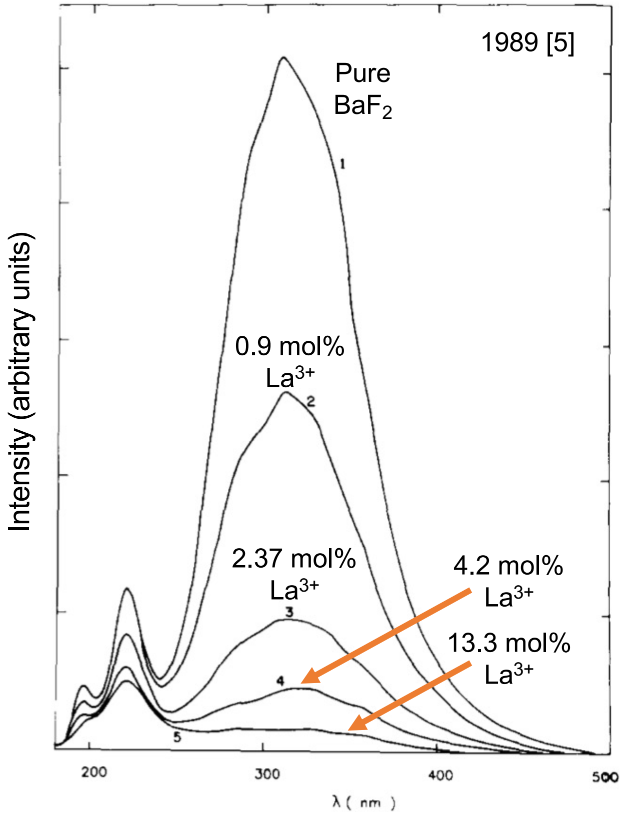
Suppression of the slow component

- **Heating** BaF_2 activates thermal dissociation of STEs



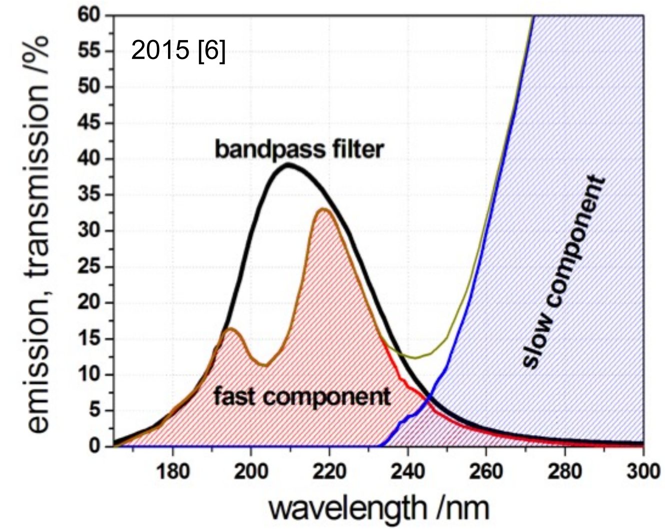
Suppression of the slow component

- **Doping** BaF_2 with rare earths preferentially quenches STE luminescence
  - Inhibits STE formation
  - Provides STE dissociation channels

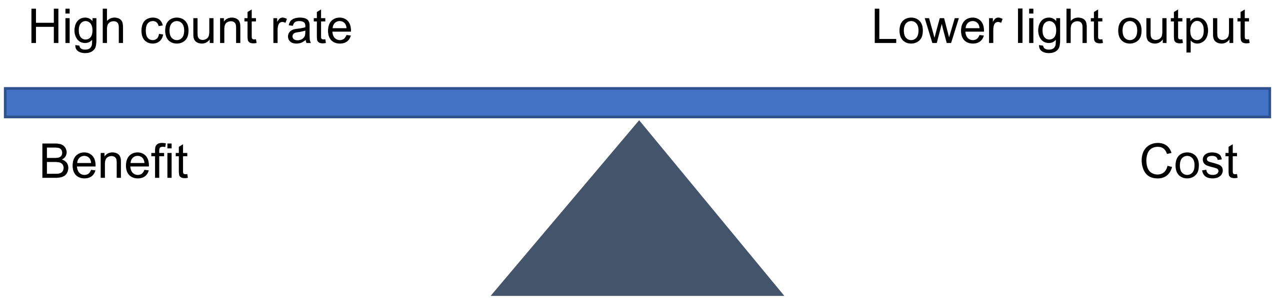


Suppression of the slow component

- **Filtering** BaF_2 emission allows selective collection of the fast component



Suppression of the slow component

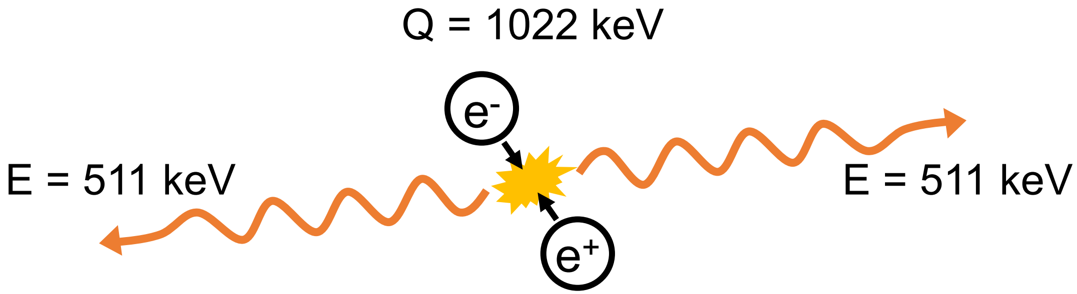


Example: HEP colliders – High bunch crossing rate and intense product showers make slow component suppression ideal.

An overview of TOF-PET

Conventional PET – Principles

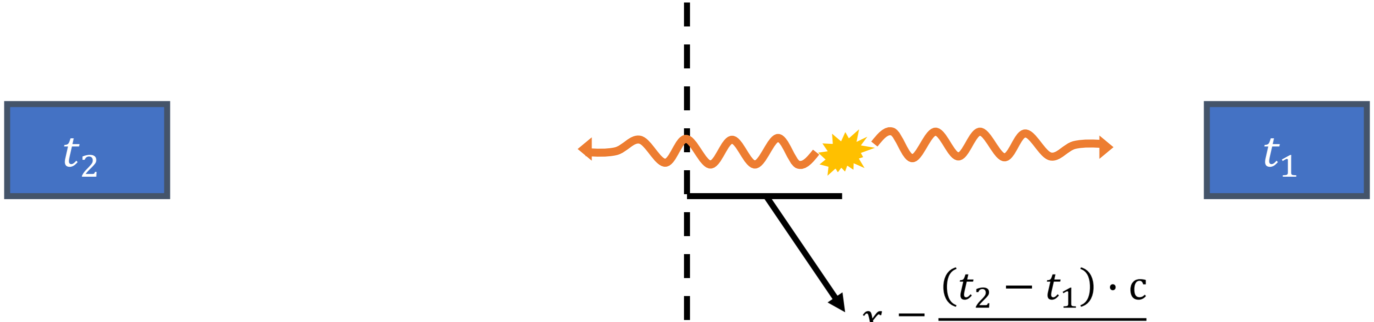
- Antiparticle pair: electrons and positrons annihilate one another, converting the rest mass of both particles into electromagnetic energy



- PET leverages these kinematics to localize a positron emitter
  - Near-coincident detection of back-to-back gammas defines a line of response (LOR)
  - Multiple LORs indicate source position via their intersection
- Conventional PET uses TOF only for event identification

TOF-PET – Principles

- TOF can localize source position along each line of response
  - The difference in time of arrival of annihilation quanta yields the distance from field of view (FOV) center to the source
- Ideally, enables direct source localization without image reconstruction
  - Obviates the need for measurements at multiple detector angles
  - Requires 1.5 mm resolution along the line of response → 10 ps FWHM coincident time resolution (CTR)

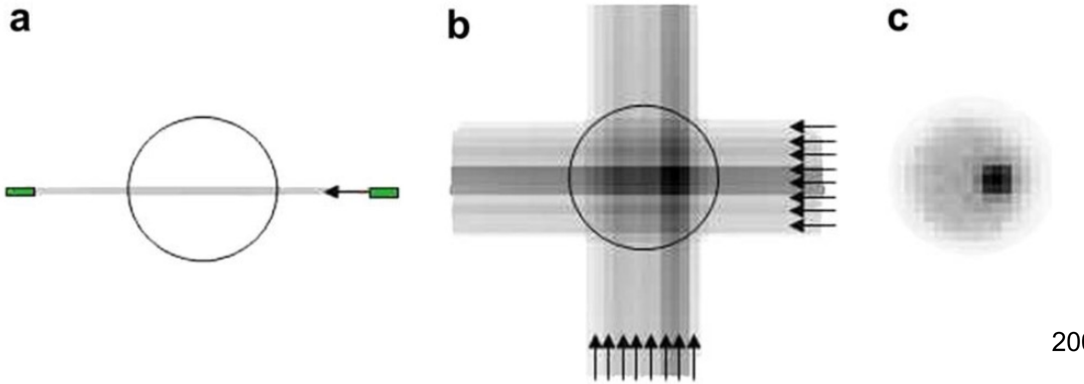


$$x = \frac{(t_2 - t_1) \cdot c}{2}$$

TOF-PET – Principles

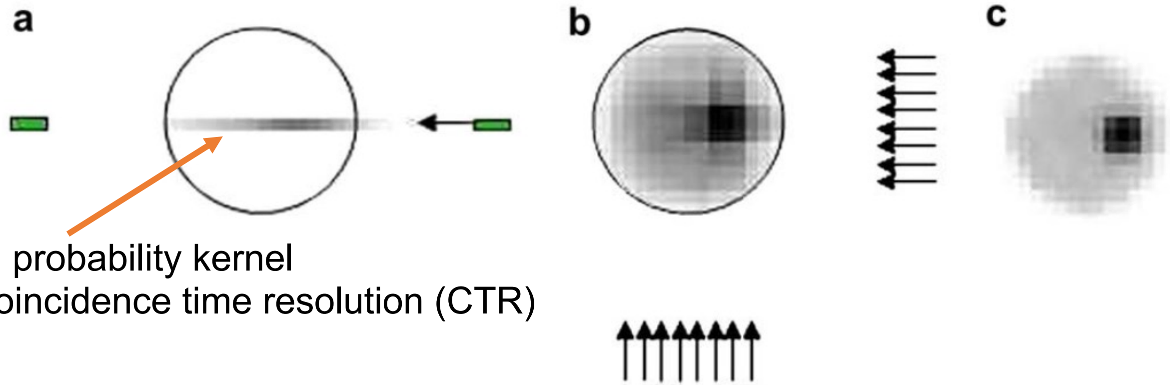
- TOF Improves image signal-to-noise ratio (SNR)

Conventional PET



2009 [7]

TOF-PET



Gaussian probability kernel
FWHM determined by coincidence time resolution (CTR)

TOF-PET – Materials

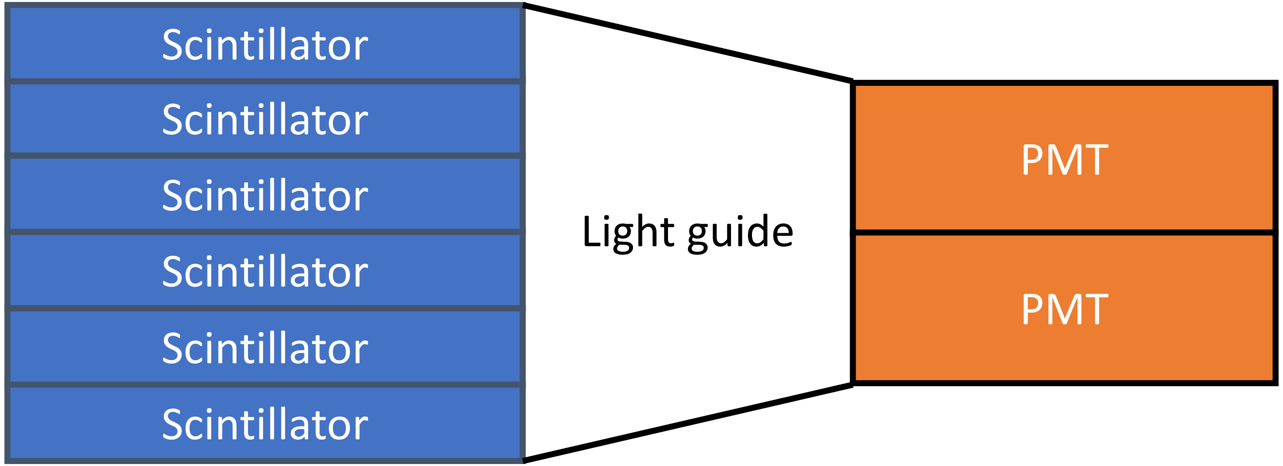
- Historically, BGO is the material of choice for conventional PET
  - TOF-PET not possible
- LSO is considered the best scintillator overall for PET
  - 300 ps CTR for two crystals → TOF-PET feasible

Property	BaF2	LSO:Ce	BGO
Density ρ (g cm^{-3})	4.88	7.4	7.13
Effective atomic number, Z_{eff}	53	66	75.2
Photon absorption α @511 KeV (cm^{-1})	0.085	0.28	0.336
Radiation length X_0 (cm)	2	1.1	1.12
Intrinsic light yield, LY_{intr} (ph/MeV)	1400[a b h]–7000[b i]	40 000[b]	10 000[b]
Decay time τ (ns)	0.6–0.8[h]/620[i]	22/44[b]	46/365[b]
Photon fraction @ 0.5 MeV	0.19[c])	0.34[c]	0.43[c]
Emission peak(s) λ_{max} (nm)	195[i] 220[i] 310[h]	420[b]	480[b]
Refractive index (RI) @ λ_{max}	1.56[d] 1.55[d] 1.50[d]	1.82[b]	2.1[b]
Melting point (°C)	1280[e]	2150[f]	1050[f]
Cost ($ cm^{-3})	15[g]	60[g]	35[g]

2021 [8]

TOF-PET – Detector structure

- Block detector
  - Tightly packed array of crystals, separated by reflective material
  - Monolithic light guide
  - Array of PMTs
  - Interaction position reconstructed from light intensity ratios across PMT array



TOF-PET – Problems with BaF_2

- Earliest TOF-PET systems utilized BaF_2, but material property difficulties and the advent of BGO all but halted development
- Low density, low effective Z
  - Poor efficiency
- Low light output
  - Poor energy resolution (photopeak identification)
  - Poor position reconstruction assuming standard block detector
- UV emission
  - Light collection challenges

Prototype development

Design considerations

Goal: Develop a pixelated BaF_2 test bed to characterize the performance of various configurations for timing applications.

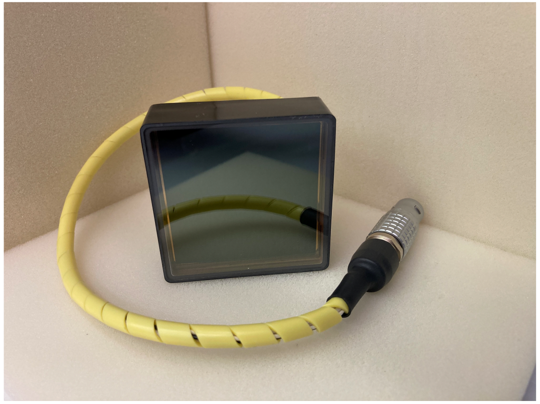
- Focus: TOF-PET → design inspiration
- Deployable form factor
- Variable system geometry

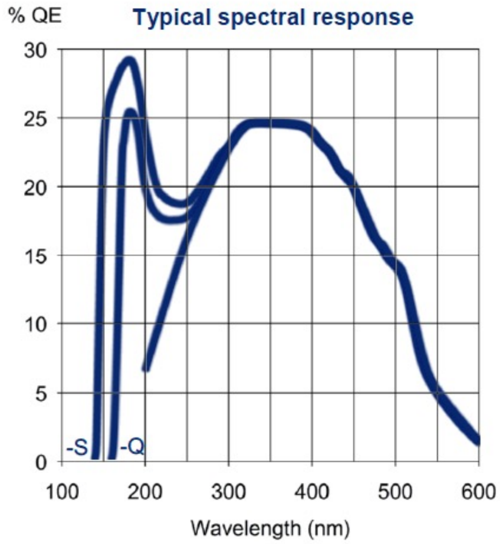
- Low density, low effective Z
  - Larger pixels
- Low light output
  - Read out each pixel individually
- UV emission
  - Total internal reflection
  - UV sensitive photodetector

- High time resolution
  - Total internal reflection
  - Low transit time spread photodetector
- Modular
  - Easily configurable experimental geometries

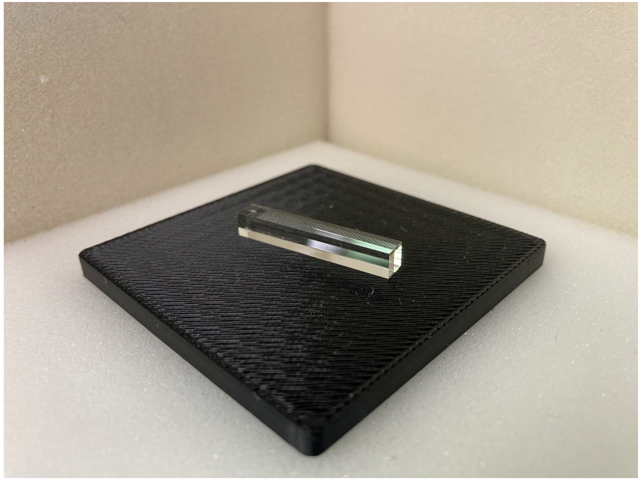
Photonis Planacon

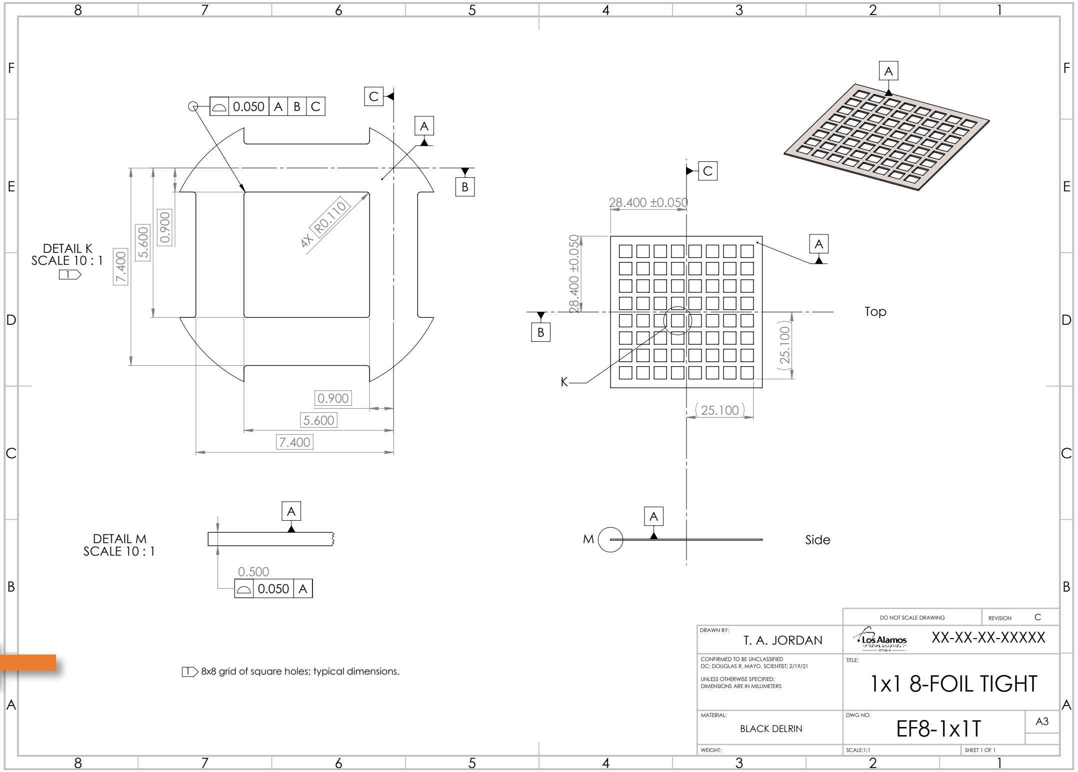
- 59 mm x 59 mm x 21 mm
- Sapphire window → Good UV transmission
- MCP gain stage
  - 35 ps transit time spread
- 8x8 grid of anodes
  - 5.9 mm square anodes, 6.5 mm pitch
- Two Samtec QRM8 connectors for signal transmission
- Potted HV divider (SHV to multi-pin LEMO)





BaF$_2$ array – Pure BaF$_2$ pixels, 4.6 mm x 4.6 mm x 30 mm

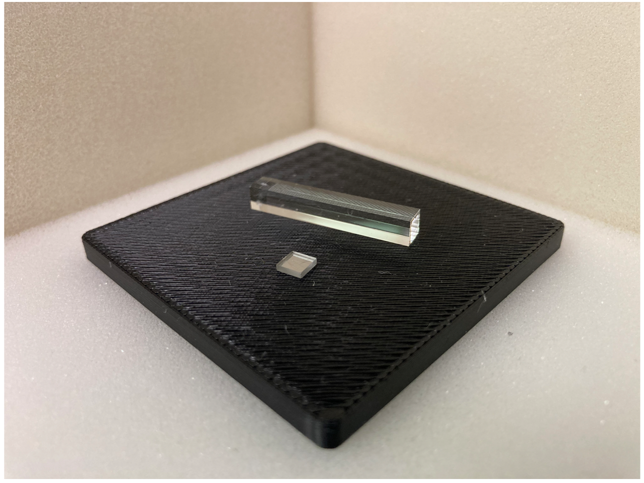




- Stack plates to form a 3D pixel frame
- Rounded corners on pixel slots enforce an air gap around each pixel
- Align pixels over anodes
- Laser-cut black acetal

Slow component suppression

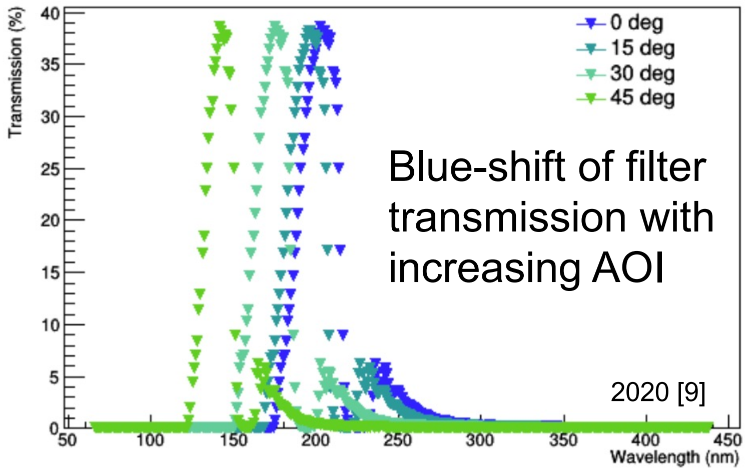
- Slow component suppression does not necessarily improve TOF-PET performance
- Instead, facilitates system characterization for high count rate applications
  - Slow component suppression via heating isn't practical for instrumentation
  - Doping can also degrade fast component intensity
  - Optical filtering is relatively easy to implement
- Interference filters can be manufactured to match pixel size, preserving optical segmentation
- Complication: filter transmission is angle-of-incidence (AOI) dependent

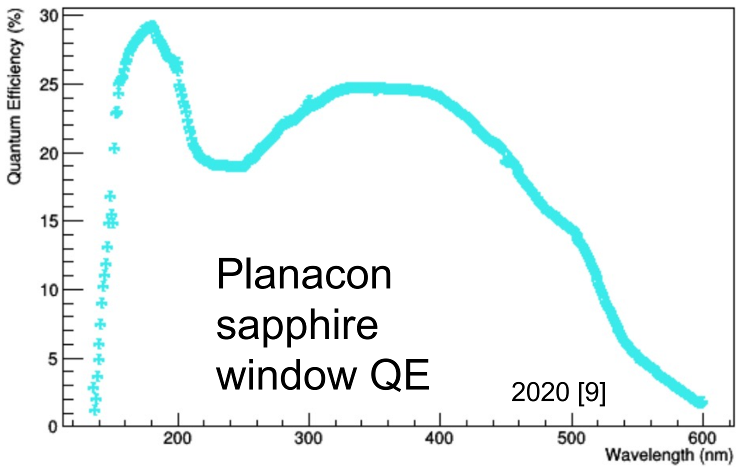


Filter optimization

- Choice of long wavelength cutoff must account for AOI distribution of collected light
- Simplified 2D light transport, AOI-dependent filter transmission, and QE calculations employed to optimize long wavelength cutoff for fast photoelectron production

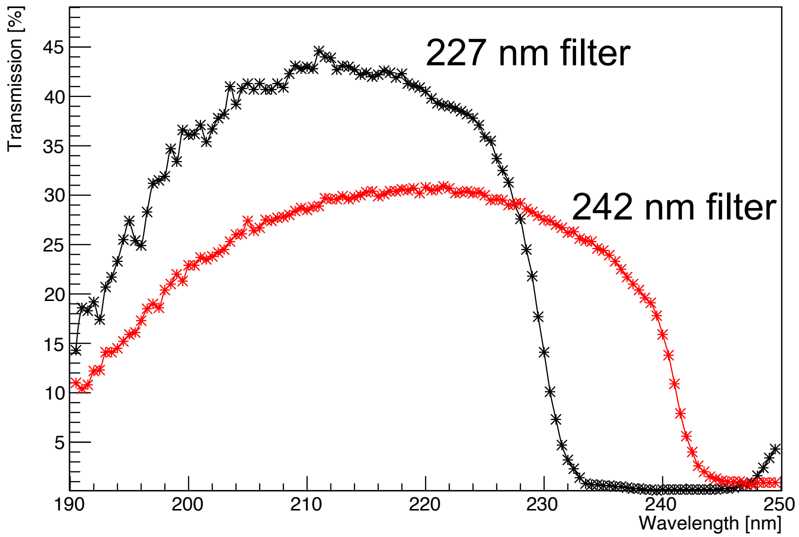
$$\lambda_\theta = \lambda\sqrt{1-\left(\frac{n_0}{n_{eff}}\sin\theta\right)^2}$$





Filter optimization

- Increasing the filter cutoff from 227 nm to 242 nm preserves more off-angle fast light, at the cost of slightly more slow component transmission
- Slow component suppression via doping would allow for an even higher cutoff

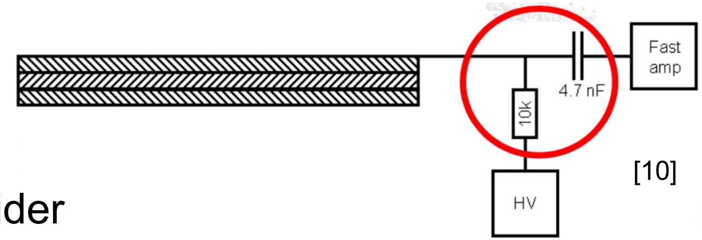


Long wavelength cutoff	Number of fast photoelectrons (pe)	[Fast pe] / [Total pe]
227nm	1.74 / MeVee	0.999
242nm	8.17 / MeVee	0.985

2020 [9]

DAQ Electronics

- Timing: CAEN VX1290N-2eSST TDC
  - 16 channels
  - 25 ps resolution
  - Timing signal can be picked off from the HV divider
    - Modify HV divider provided by Photonis (if possible)
    - Design custom HV divider
  - A 10 ps resolution model coming soon…
- Spectroscopy: CAEN VX2740 digitizer
  - 64 channels
  - 125 MS/s → 8 ns samples
  - 2 V full scale range, 16-bit
  - Spectroscopy helps with event identification in TOF-PET



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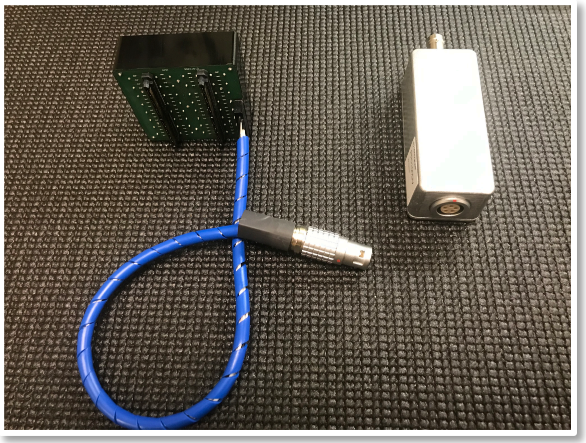
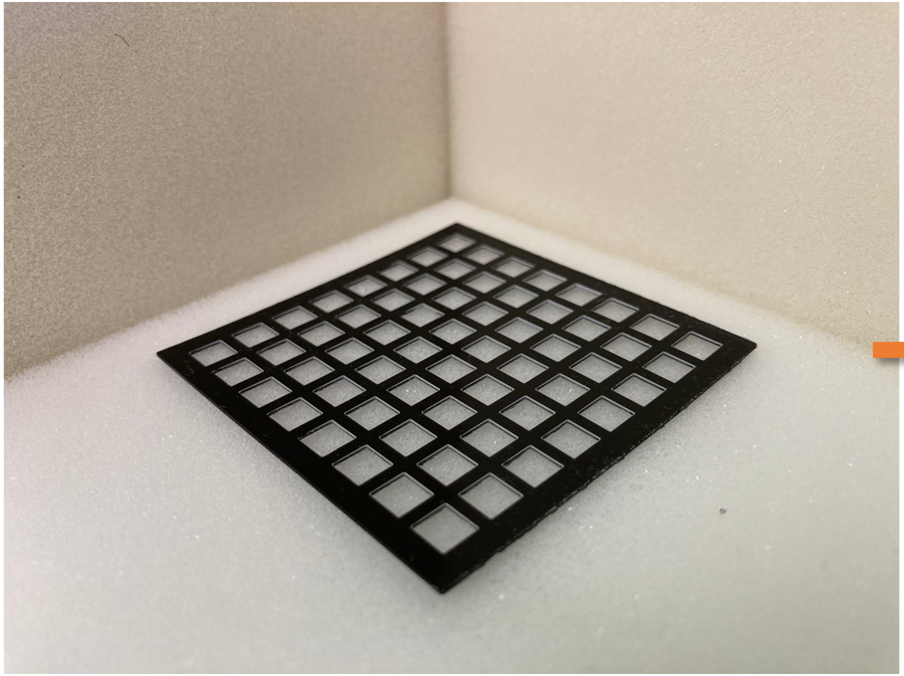
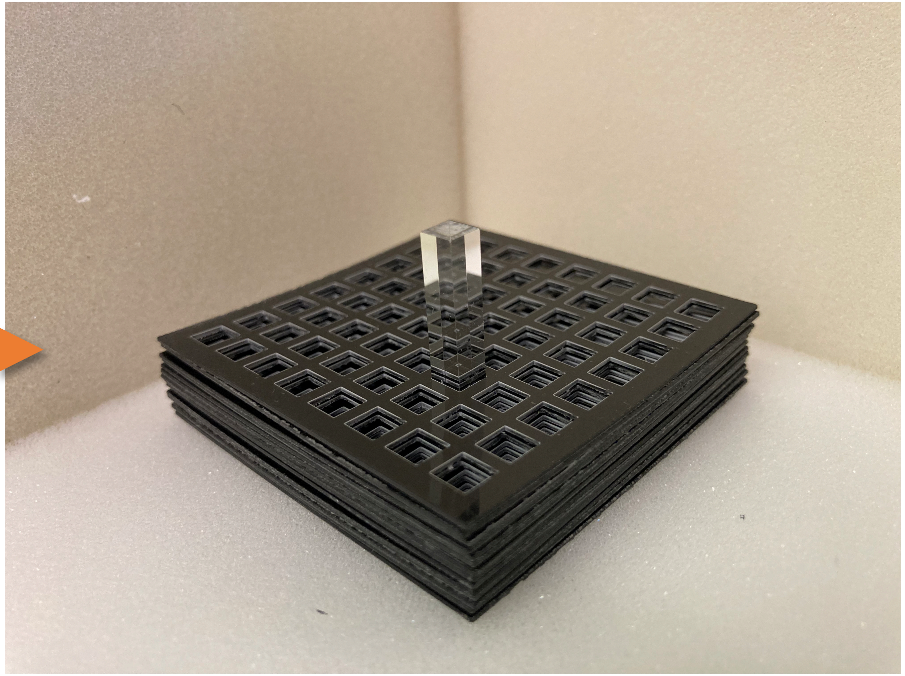


Detector assembly

BaF_2 array construction

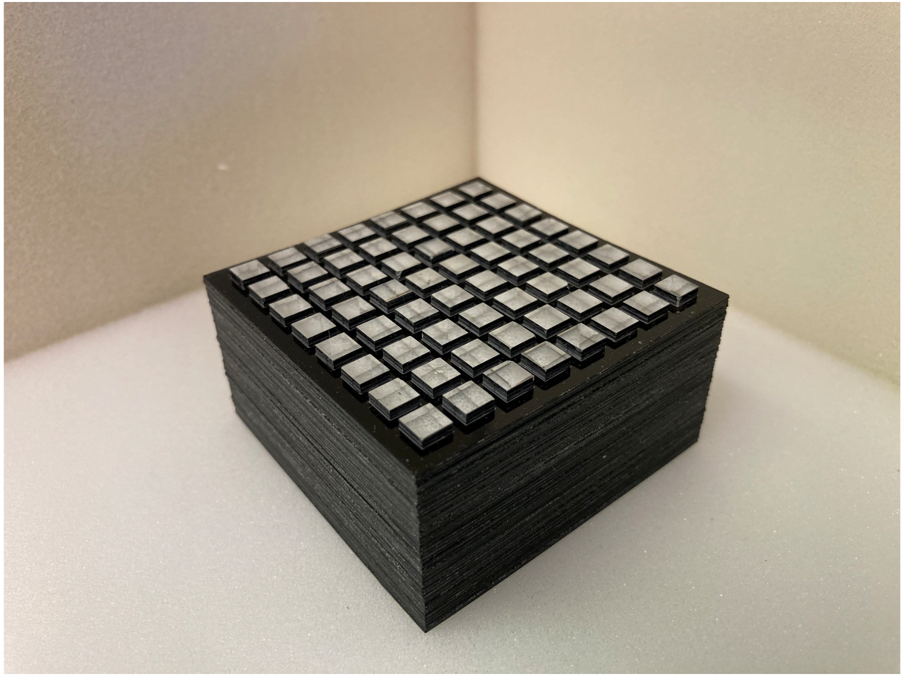
- ~60 plate stack forms pixel frame

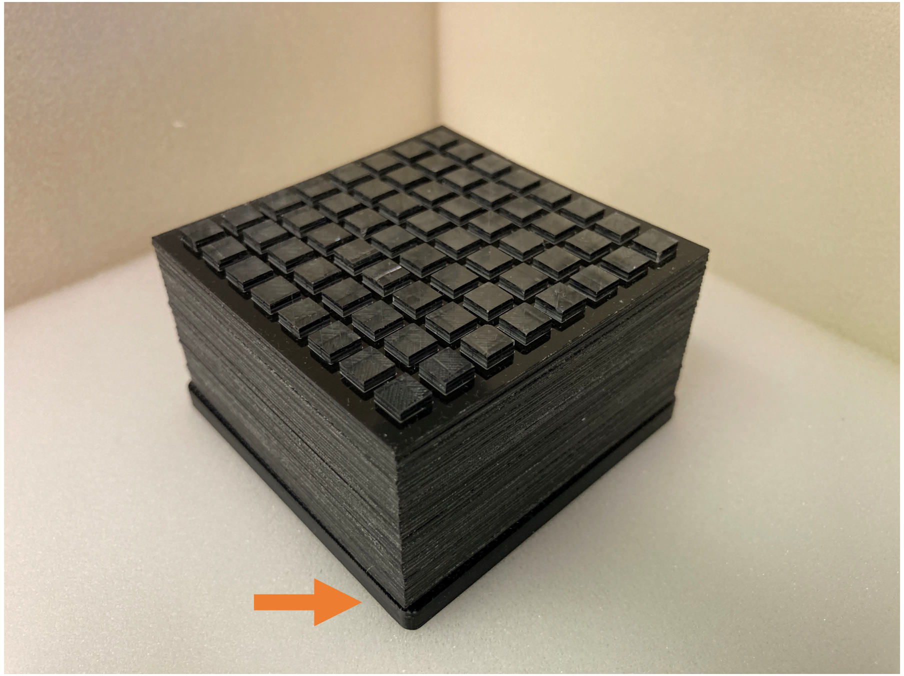




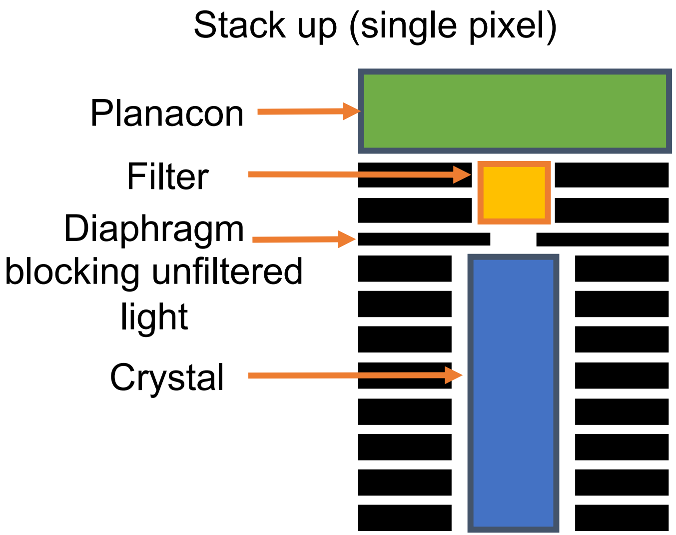
BaF_2 array construction

- Air gap around each pixel enables total internal reflection
  - The top of each pixel shows the color of the surface the array sits on

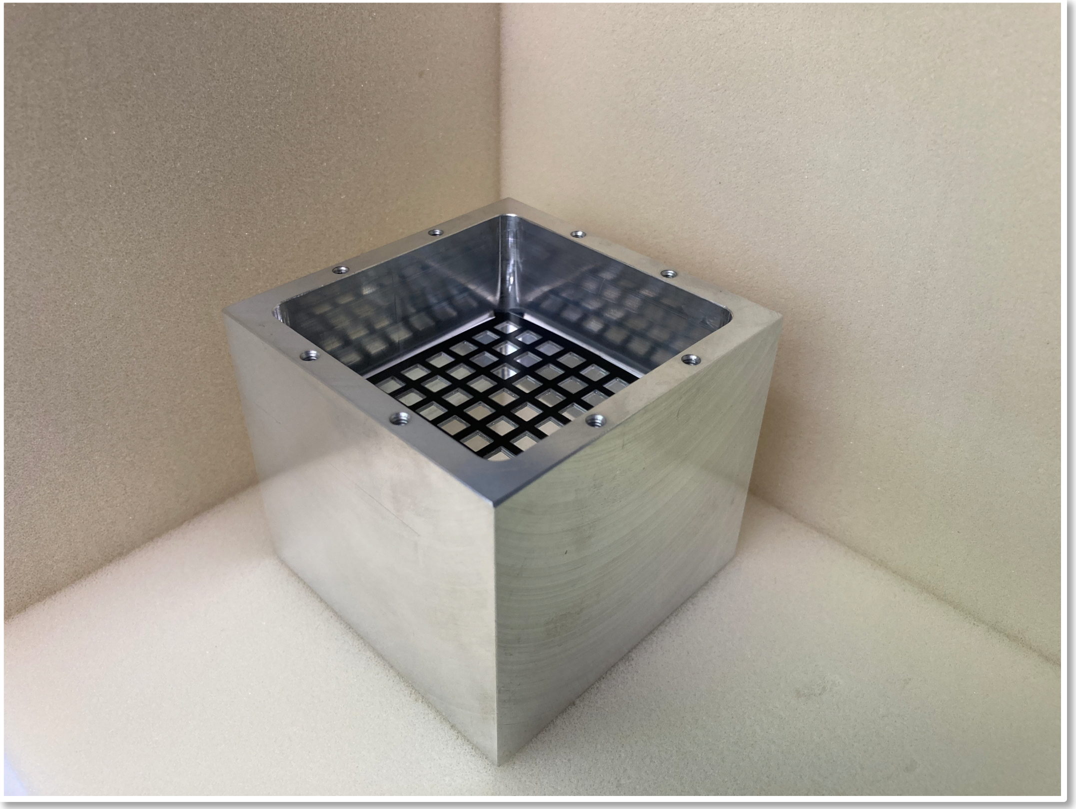




Detector assembly

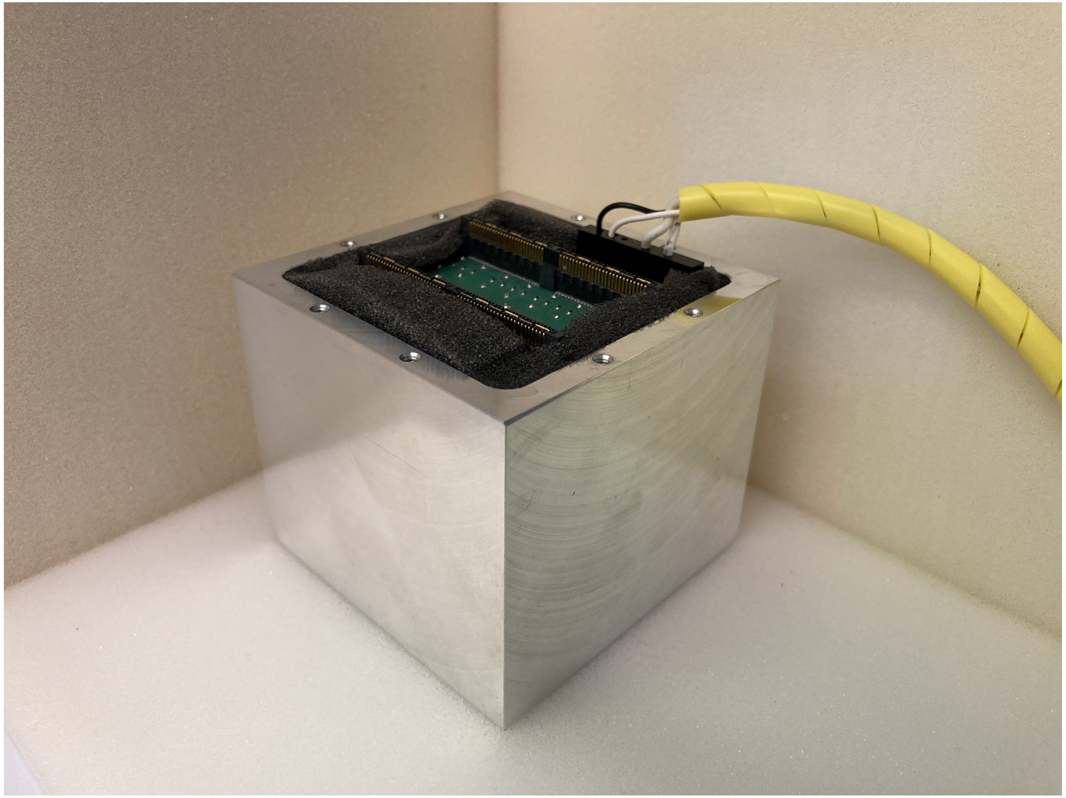


- Filtered BaF_2 array sits at the end of an aluminum housing



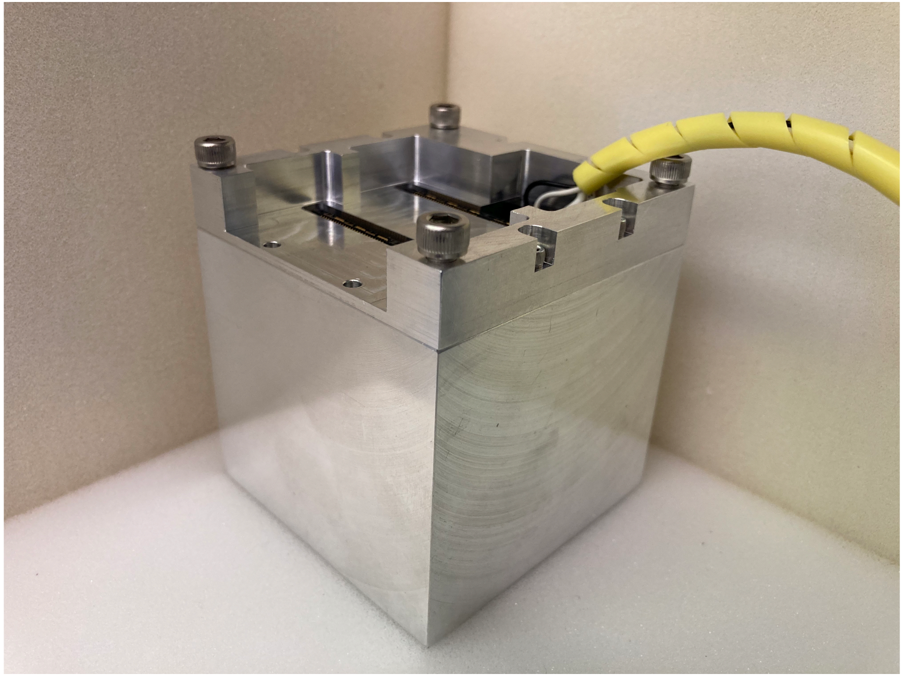
Detector assembly

- Planacon is air-coupled to the array



BaF_2 array construction

- Four corner screws for mounting
- 4 detectors assembled!



Next steps

Simulations

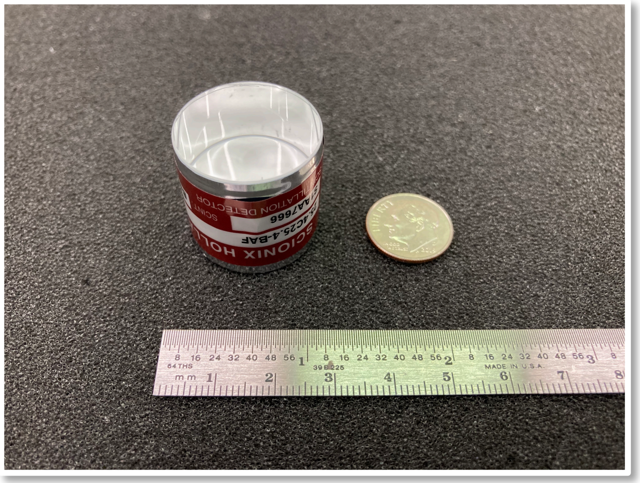
- Toy Monte Carlo models are useful for system performance estimation and building intuition, but they are not sufficient
- GEANT4: G4Scintillation and G4OpticalPhoton
  - One simulation spanning from radiation incident on a BaF_2 crystal to digitized waveforms
- Validation via comparison to experimental data enables design optimization in simulation space
  - Optimization parameters
    - Crystal dimensions
    - Crystal emission spectrum (i.e., doping)
    - Filter wavelength cutoff
    - Optical coupling

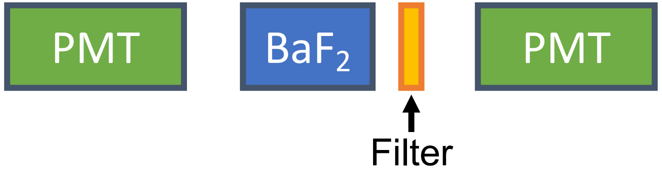
Data acquisition software

- VX2740 digitizers represent a significant departure from previous CAEN product design
  - Hardware: direct communication via USB/ ethernet rather than VME backplane
  - Software: string-based register interface rather than hexadecimal
- This is an opportunity to build new DAQ control software from scratch, rather than making discontinuous modifications to existing code
  - Must incorporate CAEN TDC, which isn’t supported by the current software
- Set up time signal pickoff from HV divider
  - Requires either existing circuit modification or custom circuit design

Experiments

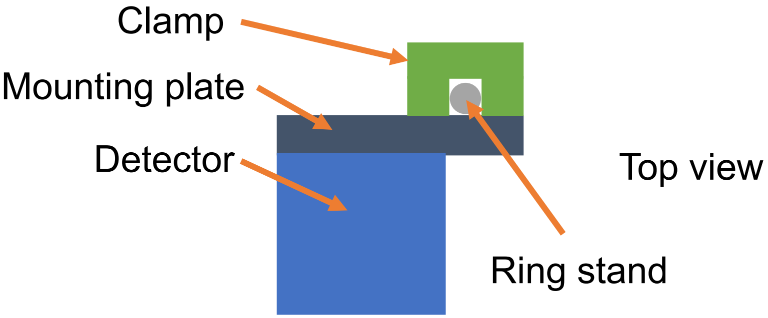
- Filter characterization
  - 1” x 1” cylindrical pure BaF_2 crystal
  - Simultaneous collection of filtered and unfiltered light leads to filtered photopeak identification
  - Feasibility study for filtered spectroscopy

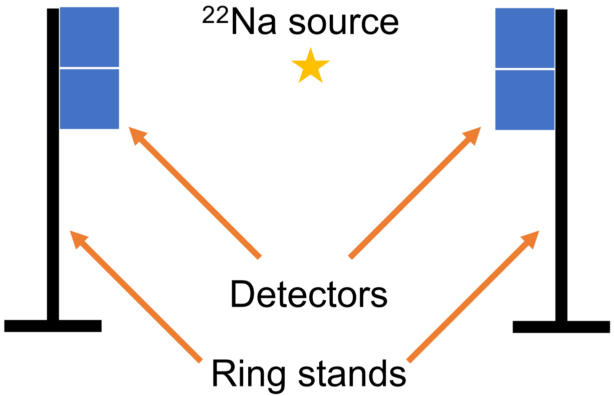


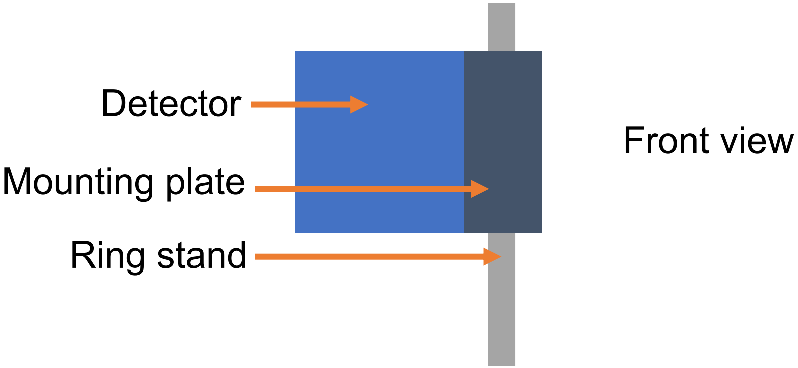


Experiments

- PET-like system performance
  - Mounting hardware to secure detectors to ring stands
  - 4 detectors have been constructed
  - ^{22}Na source localization







Final thoughts

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Los Alamos National Laboratory has provided all of the resources that made this work possible, for which I am exceedingly grateful.

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Questions?

Toy Monte Carlo models

Light transport

- N events with E energy deposited
- For each event
  - Position sampled uniformly throughout crystal
  - Number of photons sampled from Poisson distribution with mean E*TLY
  - For each photon
    - Emission component sampled according to FLY/TLY
    - Emission time sampled from exponential distribution
    - Wavelength sampled from digitized spectrum
    - Direction sampled isotropically
      - Photons moving the wrong way are thrown out
    - Time to hit crystal face in each direction computed from position and direction
    - Indices of refraction and critical angles computed from wavelength

Light transport

- Based on times and TIR criteria, the following are calculated
  - Collected (bool)
  - TIR at collection face (bool)
  - AOI on collection face
  - Refracted AOI after escaping through collection face
  - Transit time in crystal
  - Collection time (emission time + transit time)
  - Number of reflections

Filter transmission

- For each photon
  - Uncollected photons are thrown out
  - Effective photon wavelength calculated from wavelength and RCAOI, according to transmission AOI dependence
  - Photons with effective wavelength outside of digitized transmission range are thrown out
  - Transmitted (bool) sampled according to probability at effective wavelength

Quantum efficiency

- Runs off of either light transport or filter transmission output
- For each photon
  - Uncollected/ untransmitted photons are thrown out
  - Photons with wavelength outside of digitized QE range are thrown out
  - Converted (bool) sampled according to probability at wavelength

Schematics

Signal cabling – QRM8 to JTAG

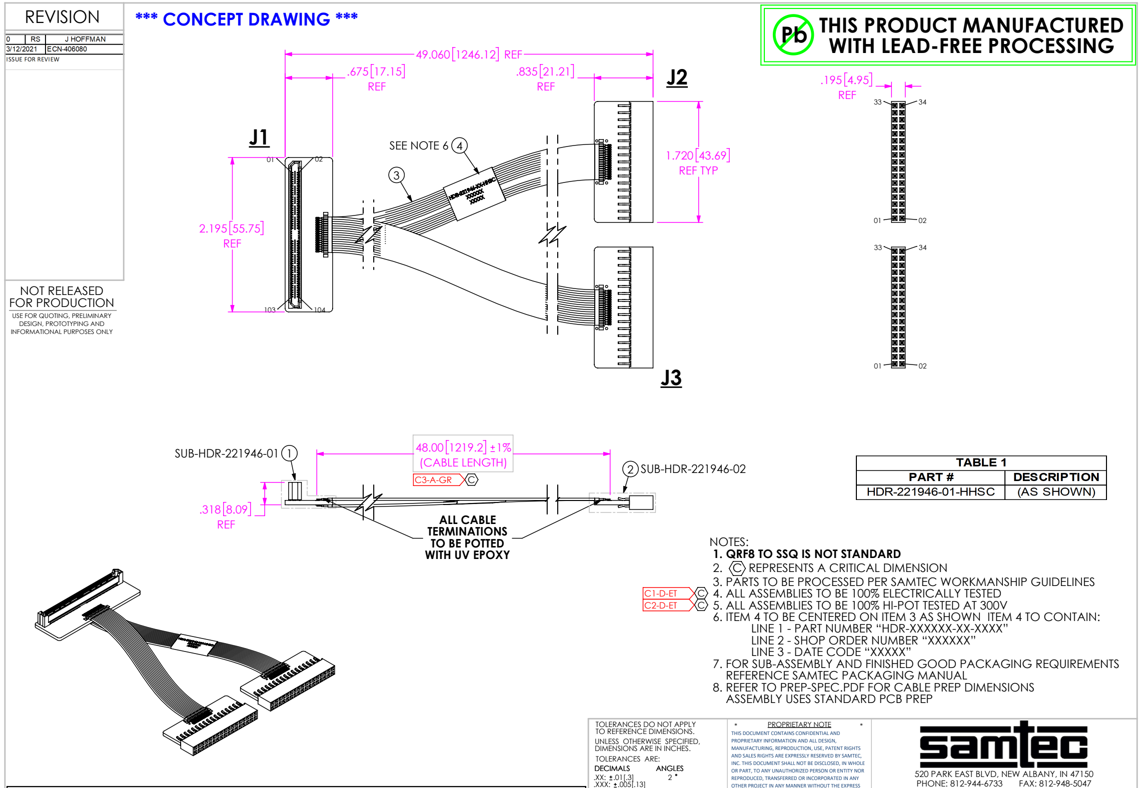


TABLE 1

PART #	DESCRIPTION
HDR-221946-01-HHSC	(AS SHOWN)

HDR-221946-XX-HHSC BOM

ITEM NO.	PART NUMBER	DESCRIPTION	QUANTITY	MATERIAL
1	SUB-HDR-221946-01	SUB ASSEMBLY	1	SUB ASSEMBLY
2	SUB-HDR-221946-02	SUB ASSEMBLY	2	SUB ASSEMBLY
3	SUB-TCF-3450-16-01-XX.XX	COAX CABLE	2	SUB ASSEMBLY
4	HDRL-11	LABEL	1	SELF LAMINATING VINYL

Signal cabling – QRM8 to MCX

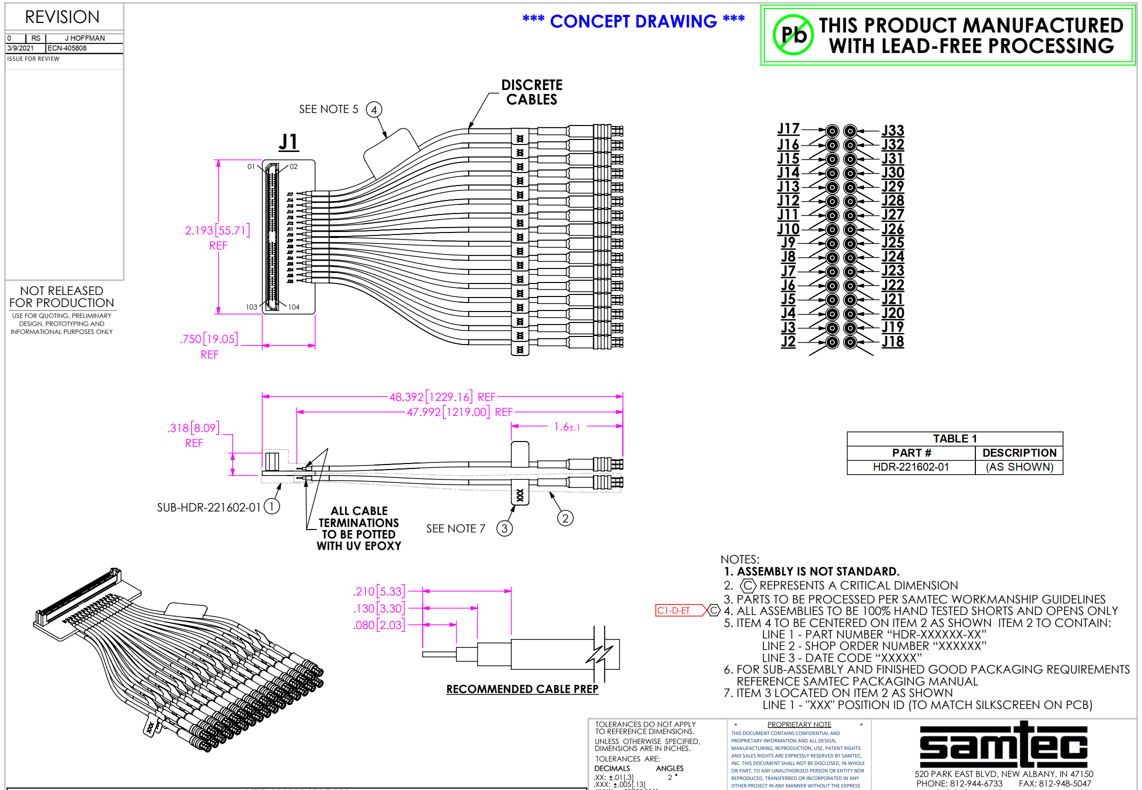


TABLE 1

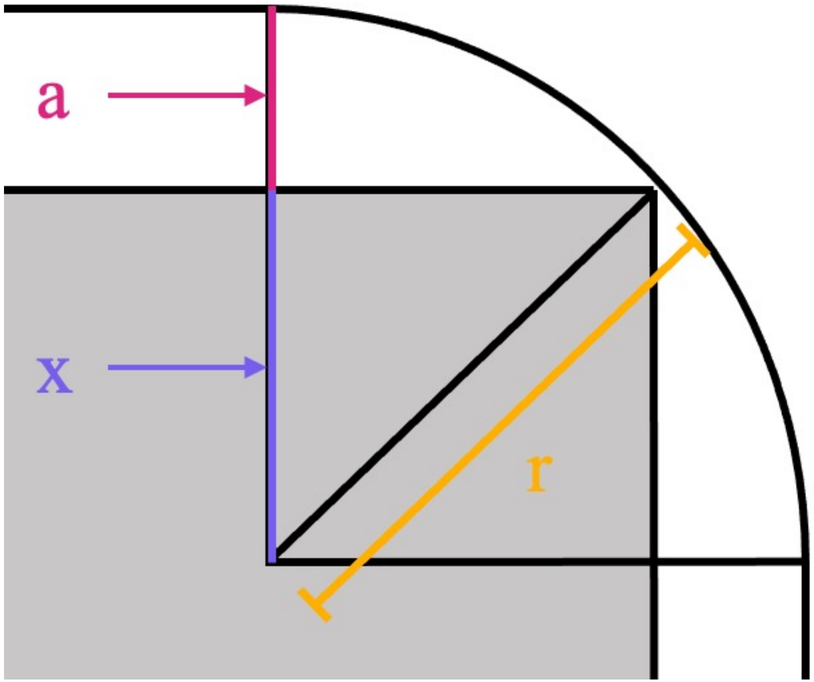
PART #	DESCRIPTION
HDR-221602-01	(AS SHOWN)

HDR-221602-XX BOM

ITEM NO.	PART NUMBER	DESCRIPTION	QUANTITY	MATERIAL
1	SUB-HDR-221602-01	SUB ASSEMBLY	1	SUB ASSEMBLY
2	RF178-02SP1-SING-1219	SUB ASSEMBLY	32	SUB ASSEMBLY
3	HDRL-16	LABEL	32	SELF LAMINATING VINYL
4	HDRL-11	LABEL	1	SELF LAMINATING VINYL

Corner radius

- Filleted corners maintain an airgap around each pixel



$$r = x\sqrt{2} \Rightarrow x = \frac{r}{\sqrt{2}}$$

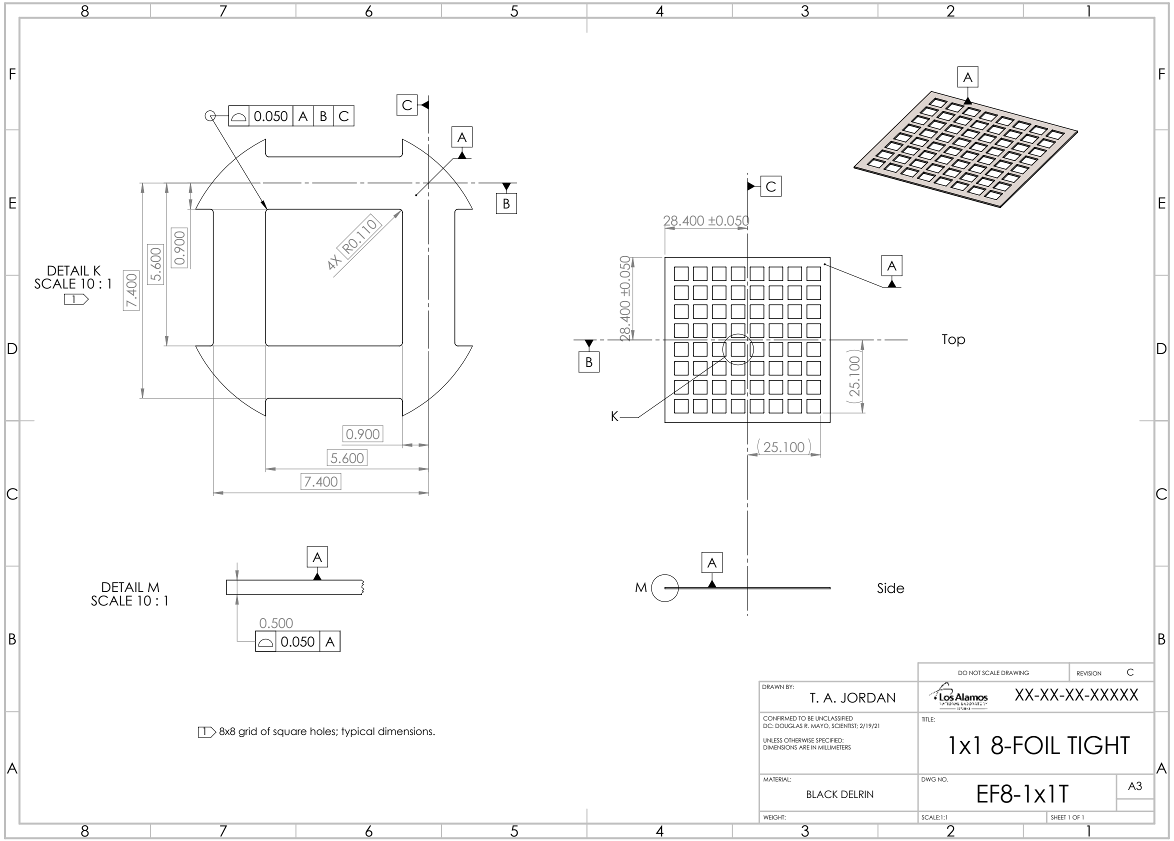
$$a + x = r \Rightarrow a + \frac{r}{\sqrt{2}} = r$$

$$\Rightarrow a = r\left(1 - \frac{1}{\sqrt{2}}\right)$$

- A slightly more complicated equation accounts for machining tolerance
- Air gap: 0.05mm
- Corner radius: 0.11mm
- Pixel size: 4.6mm
- Hole width: 4.7mm

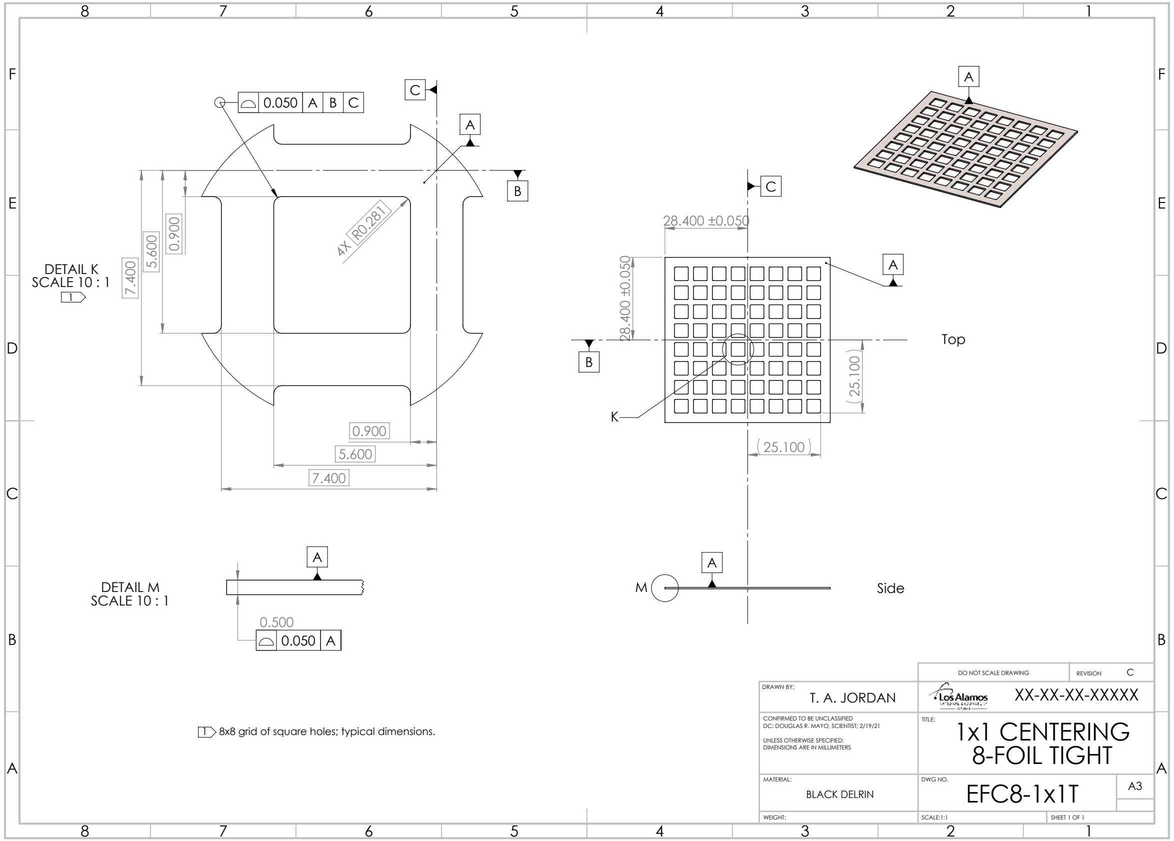
BaF_2 array structural components – pixel plates

- Stack up to form a 3D pixel frame
- Rounded corners on pixel slots enforce an air gap around each pixel
- Align pixels over anodes
- Laser-cut black acetal
  - Nonconductive material avoids potential interference with electron optics



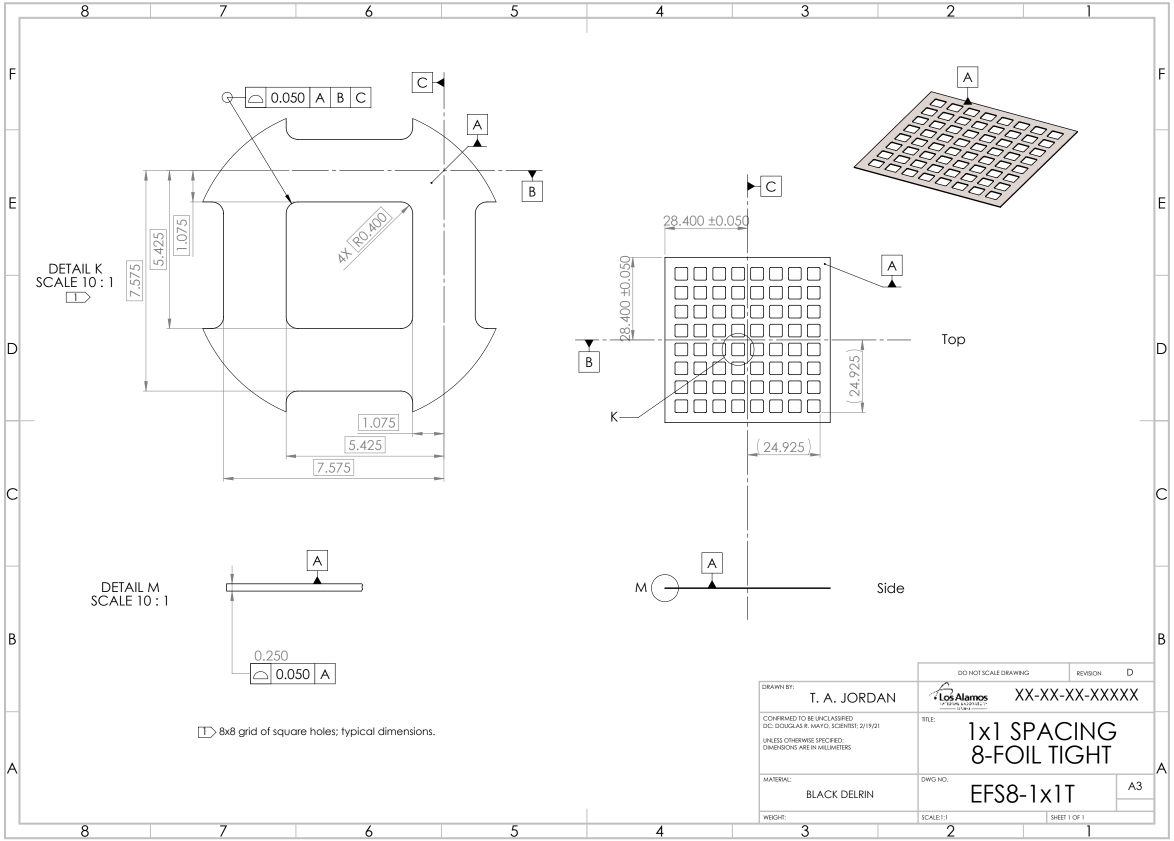
BaF_2 array structural components – filter plates

- Align filters under pixels
- Laser-cut black acetal
  - Nonconductive material avoids potential interference with electron optics



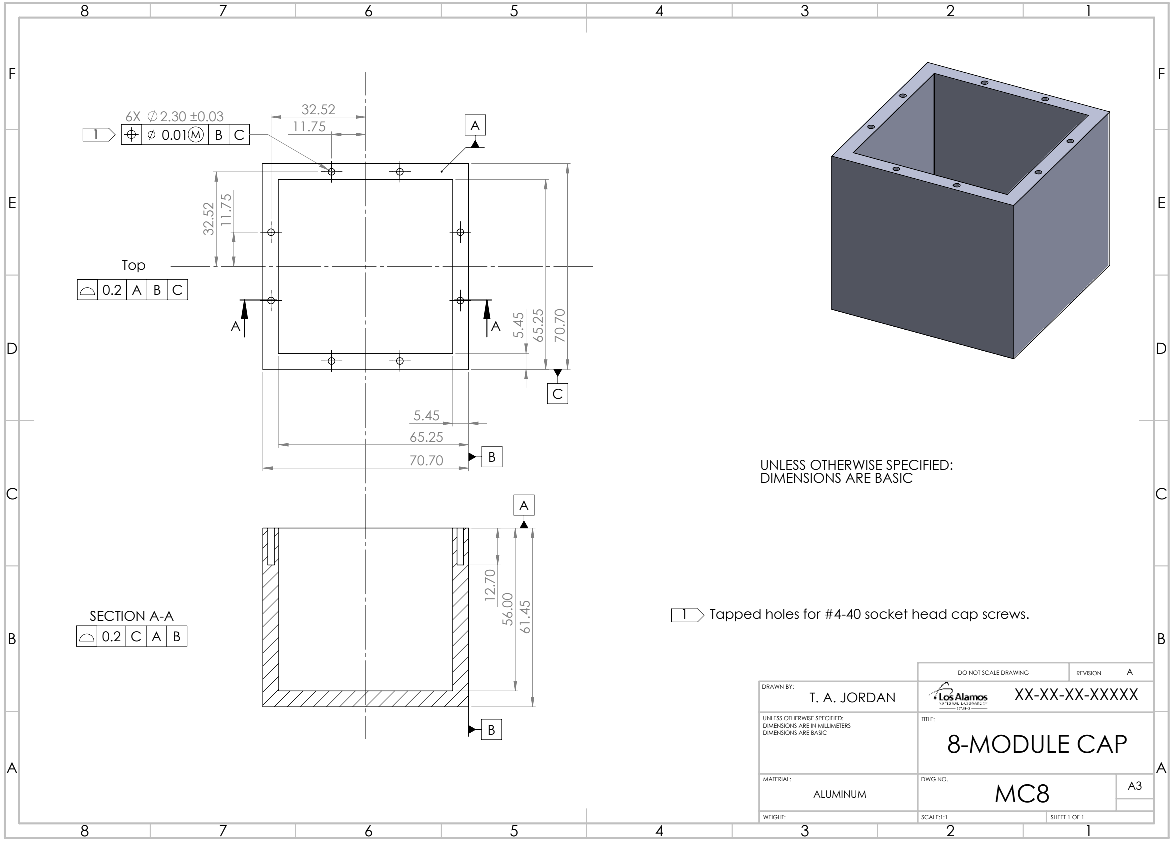
BaF_2 array structural components – spacer plates

- Diaphragm blocking unfiltered light to account for pixel-filter size mismatch
- Laser-cut black acetal
  - Nonconductive material avoids potential interference with electron optics



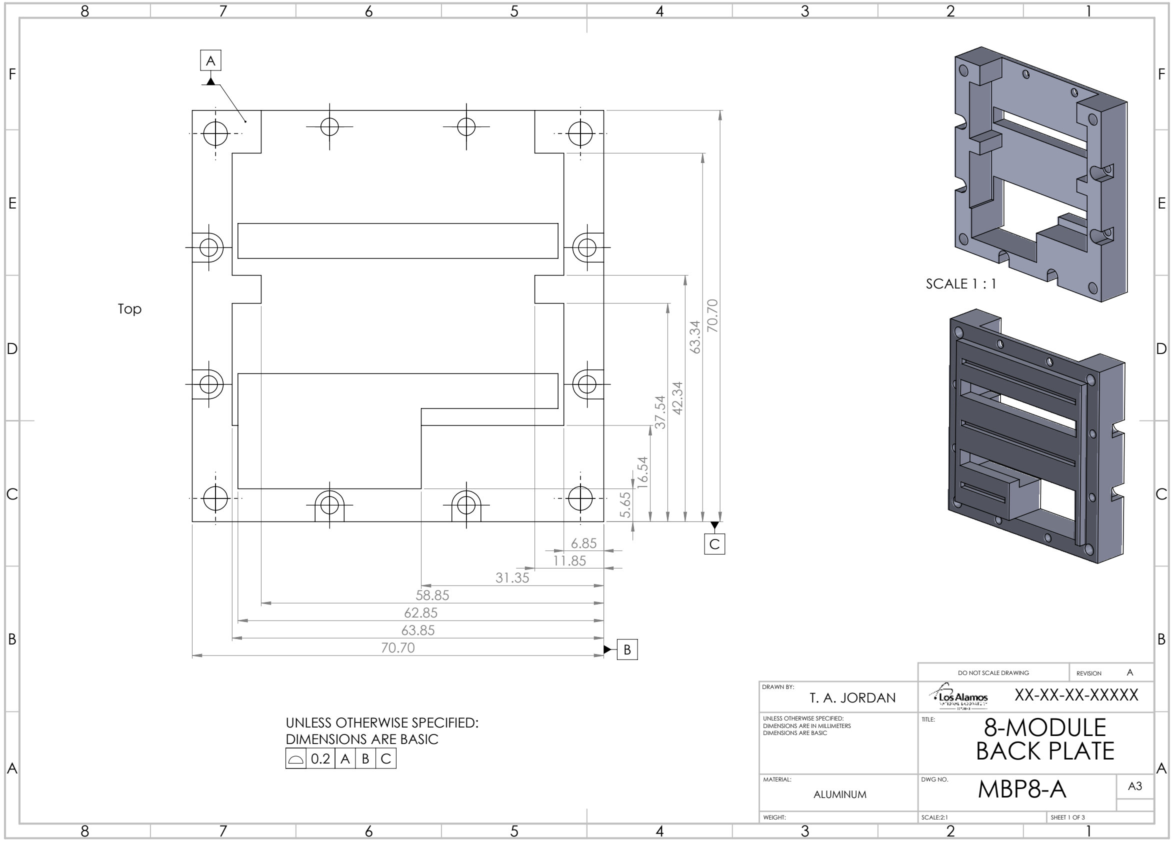
Detector housing – cap

- Contains the pixel-filter-Planacon stack-up
- Wall thickness set such that two adjacent detectors will have 3 columns of "dead pixels" between them
- Aluminum
  - Low Z material for minimal gamma attenuation



Detector housing – back plate

- Ports for signal and HV cables
- 4 mounting holes
  - #10-32 screws
- Aluminum
  - Low Z material for minimal gamma attenuation



Principles of radiation detection

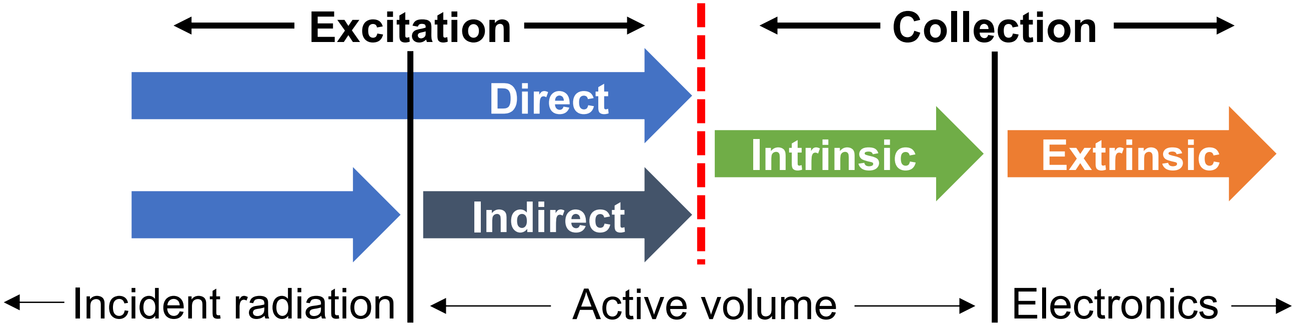
What is a radiation detector?

- A transducer that converts radiation into electric current
  - The output current encodes information about radiation interactions within the detector
- An analogy: cryptography
  - Goal: to translate information's syntax while preserving its substance
  - Physics handles the encryption
  - We are responsible for decryption, so we must understand the physics

By Hubert Berberich (HubiB) - Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=25964875

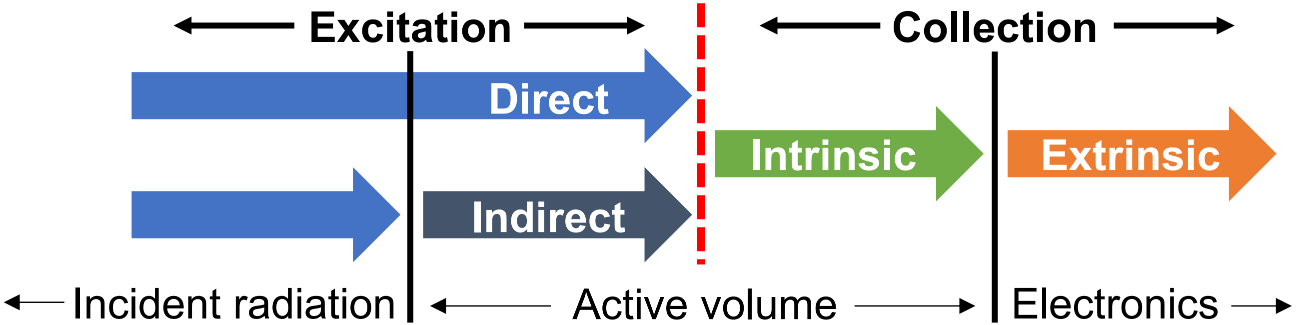
Two stages of general detector response

1. Excitation: a free, energetic charged particle interacts Coulombically with the electrons in the detector active volume
   - Direct, e.g., a decay alpha in a gas detector
   - Indirect, e.g., a photoelectron in a semiconductor detector
2. Collection: the intervening process(es) between excitation and the final output current
   - Intrinsic, e.g., scintillation
   - Extrinsic, e.g., pulse shaping



Two stages of general detector response – timing

- Extrinsic collection processes can be optimized for timing
  - Ex: high time resolution photodetectors in a scintillation detector
- Excitation time and intrinsic collection time are determined by detector material properties
  - Ex: stopping power, electron/ hole mobilities (semiconductors), fluorescence decay time (scintillators)
  - Define the fundamental limits of detector performance
- New material properties → new detectors



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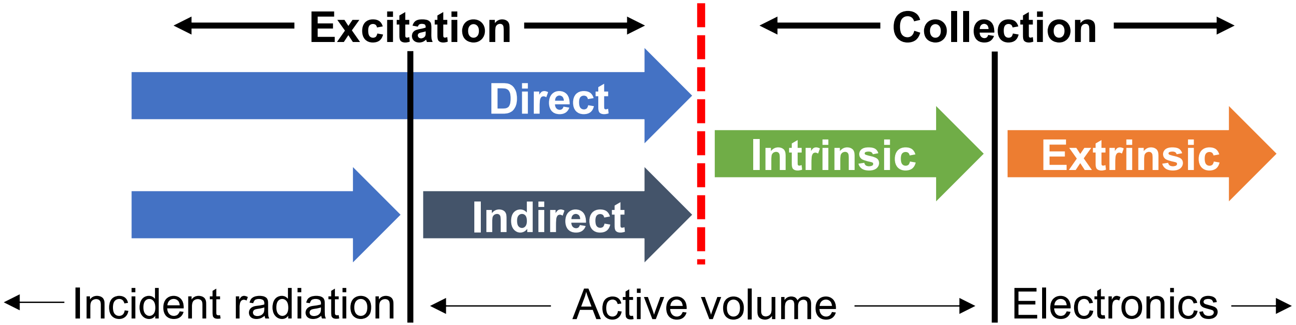
The discovery of the BaF_2 fast scintillation component prompted a wave of BaF_2 R&D

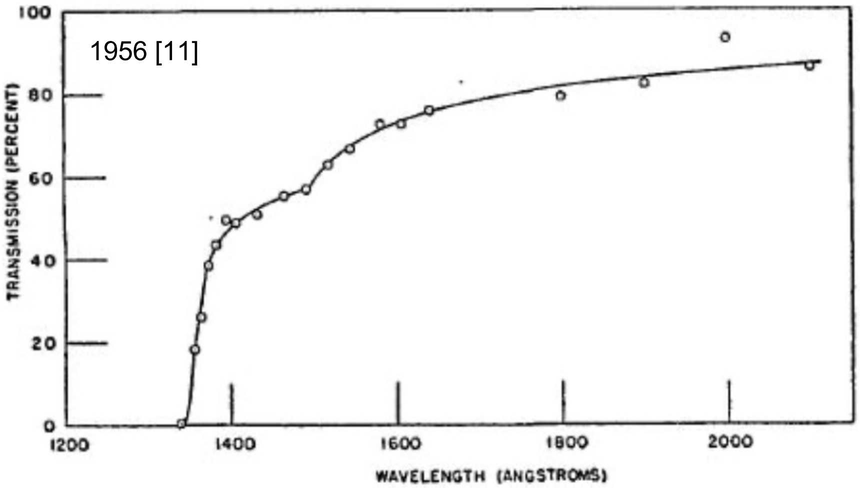
- New material properties → new detectors

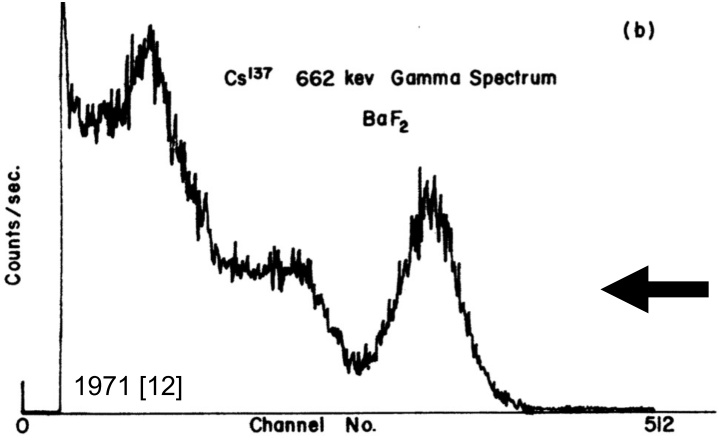


BaF_2 Timeline

A brief history of BaF_2 R&D

- BaF_2 was originally investigated for vacuum ultraviolet optical elements
  - Non-hygroscopic
  - Very slightly water soluble

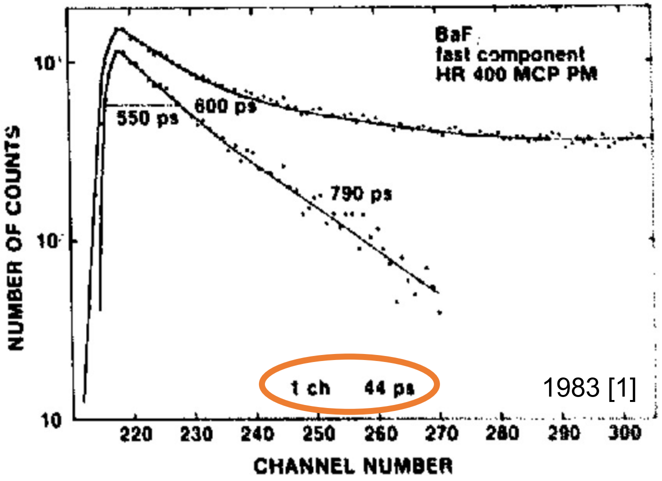




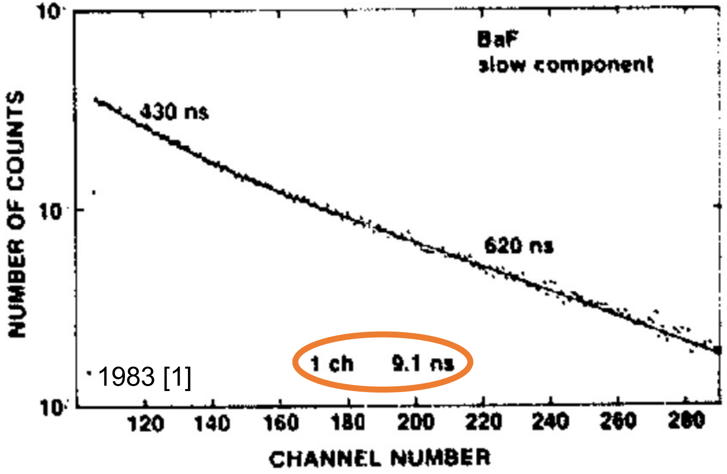
- 1971: Farukhi et al. observe scintillation under ionizing irradiation
  - Emission peaked at 325 nm
  - 630 ns decay time constant
  - Scintillation mechanism not well understood, attributed to modification of hole centers

A brief history of BaF_2 R&D

- 1971-1982: very little progress, still mostly focused on UV transmission
- 1982: Ershov et al. and Laval et al. independently observe the fast scintillation component
  - Laval et al. propose TOF-PET as a potential application



1983 [1]



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A brief history of BaF_2 R&D

- 1971-1982: very little progress, still mostly focused on UV transmission
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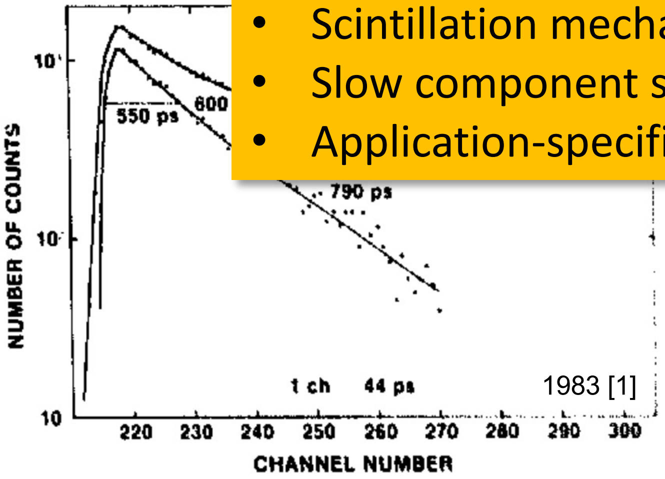
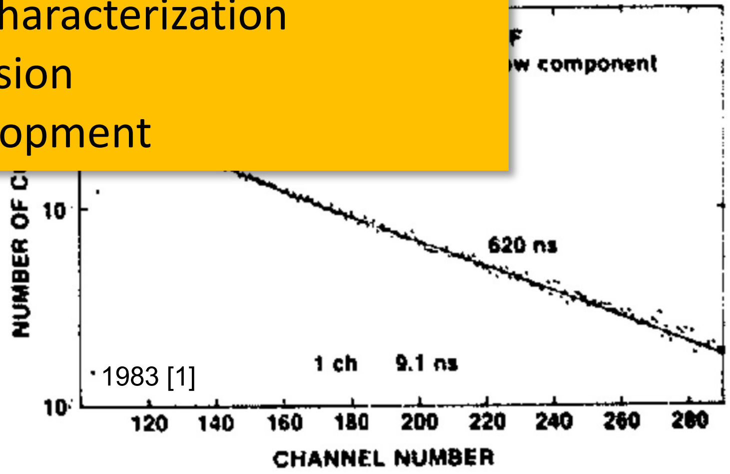
1982 onwards:
- Scintillation mechanism characterization
- Slow component suppression
- Application-specific development





BaF_2 in the 21st century

- **Medical imaging**
- **High energy physics**
- **Low energy physics**
- **Materials science**

Photodetectors
- Solar-blind PMTs
- VUV SiPMs

Doping
- La, Y, Lu, Sc
- Tm, Ce, Nd

Other applications
- Oil well logging
- Thermal neutron detection
- Double beta decay detection
- Dark matter detection

Scintillation characterization
- Discovery of “very fast” emission below 240 nm with 100 ps decay time

BaF_2-based materials
- Nanoparticles
- Ceramics
- Composites